

**Scenario Planning for U.S. Supply Chain Resilience:
Modeling the Impacts of Geopolitical Disruptions and Freight Cost Volatility**

**Scenario Planning for the Resilience of US Supply Chains: Modeling the Impacts of Geopolitical Disruptions
and Freight Cost Volatility**

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Summary

This article examines the use of **scenario planning** as a decision-making tool to strengthen the **resilience** of U.S. supply chains in the face of **geopolitical disruptions** (sanctions, conflicts, embargoes, regulatory shocks) and **freight cost volatility** (ocean, rail, road, and air). The paper integrates the **operations and risk** literature with **strategic intelligence** practices, proposing a method that links **plausible narratives** to **quantitative models** (discrete event simulation, system dynamics, and Monte Carlo), producing metrics for **TTS/TTR**, **OTIF**, **Operational VaR**, and **avoided loss** under different trajectories. The paper argues that the usefulness of scenarios increases when coupled with **signposts** and **decision triggers** that activate **contractual optionalities**, **structural buffers**, and **multi-gateway rerouting**. Evidence from industry reports and public policy frameworks—such as the **National Freight Strategic Plan** (USDOT)—suggests that the combination of **modular architecture**, **interorganizational data**, and **option-based contracts**

reduces the area of the **resilience triangle** and protects margins in shocks (SHEFFI, 2015; CHOPRA; MEINDL, 2016; USDOT, 2020; UNCTAD, 2020; SEA-INTELLIGENCE, 2021).

Keywords: scenario planning; resilience; freight costs; geopolitics; TTS/TTR; United States.

Abstract

This paper examines **scenario planning** as a decision tool to strengthen the **resilience** of US supply chains against **geopolitical disruptions** (sanctions, conflicts, embargoes, regulatory shocks) and **freight cost volatility** (ocean, rail, truck, air). We integrate **operations and risk** literature with **strategic foresight** practices, proposing a method that links **plausible narratives** to **quantitative models** (discrete-event simulation, system dynamics and Monte Carlo), yielding **TTS/TTR**, **OTIF**, **Operational VaR** and **loss avoided** under alternative paths. We discuss scenarios are more useful when coupled with **sign posts** and **decision triggers** that activate **contractual options**, **structural buffers** and **multi-gateway rerouting**. Evidence from industry

reports and policy frameworks—such as the **National Freight Strategic Plan**—suggests that combining **modular architectures, inter-organizational data, and option-based contracts** reduces the **resilience triangle** area and protects margins under shocks (SHEFFI, 2015; CHOPRA; MEINDL, 2016; USDOT, 2020; UNCTAD, 2020; SEA-INTELLIGENCE, 2021).

Keywords: scenario planning; resilience; freight costs; geopolitics; TTS/TTR; United States.

1. Fundamentals and Scope: Why Scenarios for US Chains Under Geopolitics and Volatile Freight

Scenario planning was born to deal with **deep uncertainty** —the kind in which statistical extrapolations lose validity—and migrated from the energy sector to operations and risk due to its ability to **explore multiple futures** without claiming to predict specific situations (WACK, 1985; SCHOEMAKER, 1995). In US supply chains, the turbulence of the 2018–2021 period highlighted how **trade policy shocks, cross-sanctions** , and **logistical constraints** can alter **total costs** and **door-to-door times** within weeks , overcoming planned slack and disrupting **S&OP/S&OE** (SHEFFI, 2015; CHOPRA; MEINDL, 2016).

Unlike linear contingency plans, scenarios **explore combinations** of forces (geopolitics × freight × energy × climate) and **chain effects** (ports-railways-highways), offering a framework for **deciding before** the crisis what to activate **during** the crisis.

The first conceptual foundation is to distinguish **measurable risk** from **non-probabilistic uncertainty**. Freight costs have distributions that can be parameterized based on indices (spot and contracts, *bunker* and diesel), but **geopolitical disruptions** have discrete dynamics (sanctions, embargoes, conflicts, canal closures) that discontinuously shift **regimes** (UNCTAD, 2020; EIA, 2021). Scenarios allow us **to represent regimes** and **transitions**, rather than insisting on historical averages that mask **the fat tails** observed in 2020–2021 (SEA-INTELLIGENCE, 2021). In resilience terms, we think of **states** (normal, degraded, critical) and **transition times** (TTR) conditioned by mitigation policies.

The second fundamental is the **maritime-land coupling** in the North American network. Port hubs such as **LA/Long Beach, NY/NJ, Savannah, Houston** , and **Gulf** gateways feed rail corridors (BNSF, UP, CSX, NS) and **interstates** , which in turn modulate **total cost** and **delivery time** to *fulfillment centers* and factories. **Geopolitical scenarios** that alter **Asian origins** (China+1 reconfiguration, Taiwan-Strait risk) or **oceanic routes** (Suez/Panama) **propagate** to docking windows, **schedule reliability** , and truck **turn times** , requiring **network treatment**, not isolated link treatment (USDOT, 2020; NOTTEBOOM; RODRIGUE, 2021). Scenario logic, therefore, needs to **traverse interfaces**.

The third fundamental is the **economics of options**. In volatile freight environments, **contractual optionalities** (capacity reservations, multi-gateway, *box pools*, flexible *take-or-pay*) function as **operational insurance** that shifts part of the *spike* risk to ex-ante mechanisms (CHRISTOPHER, 2016; SIMCHI-LEVI; KAMINSKY; SIMCHI-LEVI, 2008). Scenarios help **price** these options based on **avoided loss** and **TTR reduction**, allowing the board to compare alternatives not only by **average cost per unit**, but also by **downside protected** in shocks—a metric more faithful to the objective of **financial resilience**.

The fourth foundation is **data governance and early warning signs**. Scenarios shouldn't be left on *slides*; they need operational and macro-level **signposts** (e.g., **persistent decline in *schedule reliability***) on trans-Pacific services, **abnormal variations** in AIS/anchorage time, **movement in sanctions** and **energy** via EIA) that **activate** pre-agreed triggers—opening **extended windows**, **diverting gateways**, **exercising capacity options**, **activating container pools** (IAPH, 2020; SEA-INTELLIGENCE, 2021). This link between **narrative-signal-trigger** is what converts scenarios into **reaction capacity**.

The fifth foundation is **regulatory and sectoral alignment**. In the US, frameworks such as the **National Freight Strategic Plan** and **continuity** guidelines (ISO 22301) reinforce the need for **intermodal cooperation**, **data standardization**, and criticality- **driven investments** (USDOT, 2020; ISO 22301, 2019). In terms of scenarios, this means considering **regulatory constraints** (hours of service, weight/height *permits*, *driver shortages*), as **theoretical options** may be unfeasible under certain rules; therefore, the **feasibility** of each response needs to be tested against **normative constraints**.

The sixth fundamental is **geographic and energy-related**. **Ocean diversions** and **air routes** in crisis alter fuel consumption and **cost curves** (bunker/diesel/jet-A), with almost immediate impact on **truckload**, **intermodal**, and **air cargo** rates (EIA, 2021; UNCTAD, 2020). Plausible scenarios should **co-simulate** energy prices and **modal capacity**, because simultaneous *spikes* in bunker and diesel prices can reduce the attractiveness of certain routes, pushing cargo onto **rail** or **aerial** and requiring **mix re-planning**.

The seventh principle is **organizational**: scenarios only produce value when **linked to S&OP/S&OE** and the **budget cycle**, with **TTS/TTR targets**, **loss limits**, and **mitigation portfolios** already approved for activation. This avoids **decision-making latency** and jurisdictional disputes amid shocks (SHEFFI, 2015; CHRISTOPHER, 2016). In other words, scenarios are **operational pre-agreements** informed by analysis, not exercises of imagination.

Finally, the eighth fundamental is **metric**: a scenario's usefulness is measured by its ability to reduce the **area of the resilience triangle** (drop × duration) and preserve **margin** and **service levels** under adverse trajectories. This requires translating narratives into **TTS/TTR**, **OTIF**, **backlog clearing**, **demurrage/detention**, **premium freight**, and **Operational VaR**, allowing for the comparison of mitigation **portfolios by impact/cost** (PONOMAROV; HOLCOMB, 2009; SIMCHI-LEVI; KAMINSKY; SIMCHI-LEVI, 2008; SEA-INTELLIGENCE, 2021).

2. Construction and modeling method: from *axes-of-uncertainty* to digital twins and *stress-tests*

The proposed method starts with the *axes-of-uncertainty framework*, mapping two to three dimensions that best explain variation in **total cost** and **door-to-door time** in US supply chains: **(i) geopolitical status** (cooperation \tilde{y} confrontation); **(ii) freight and energy** regime (stable \tilde{y} volatile with tails); **(iii) port/intermodal capacity** (unobstructed \tilde{y} congested).

The combination of these axes generates a **portfolio of extreme and intermediate scenarios** (WACK, 1985; SCHOEMAKER, 1995). For each quadrant, causally coherent **storylines** are defined: for example, "Confrontation + Volatility + Congestion" incorporates **sanctions** that displace Asian flows, bunker/diesel **spikes**, **falling schedule reliability**, and **queues** at Pacific gateways; the opposite describes detente, stable fuels, and **demand-capacity balance**.

The second step translates **storylines** into **quantifiable drivers**. For geopolitics: **tariffs** and **sanctions** in product classes, **export restrictions**, **partial canal closures**, and **security rules**; for freight/energy: **bunker/diesel/jet-A curves** and tariff elasticities by mode (UNCTAD, 2020; EIA, 2021); for capacity: **schedule reliability** by service, **queue/berthing time**, **quay productivity**, and **truck/rail turn times** (SEA-INTELLIGENCE, 2021; WORLD BANK, 2020). These drivers feed **coupled models** that will represent **propagation** (maritime \tilde{y} port \tilde{y} hinterland) and **response** (buffers, diversion, options).

The third step is to select **modeling tools**. **Discrete Event Simulation (DES)** represents interconnected queues at the pier, yard, gate, and rail; **system dynamics (SD)** captures stocks/flows and **feedbacks** (bullwhip effect, accumulated backlog); **agent-based models (ABM)** introduce **adaptive behaviors** (rolling, SLA-based prioritization, route selection by drivers/operators) (IVANOV; DOLGUI, 2020; CHOPRA; MEINDL, 2016). **Monte Carlo** adds **variability** to the drivers (price, reliability, arrival), producing **probabilistic ranges** of TTR and cost. In practice, a **digital twin** of the trans-Pacific or trans-Atlantic corridor integrates DES+SD+ABM with **AIS/TOS/PCS data**.

The fourth step defines **output metrics** that matter to the decision maker: **TTS/TTR** per node/corridor, sea-to-land **OTIF**, **backlog clearing time**, **demurrage/detention**, **freight premium**, and **preserved margin**. Additionally, **Operational VaR** (expected tail loss) and **Expected Shortfall** are calculated under each scenario, allowing for comparison of mitigation **portfolios** by **avoided loss per dollar** (PONOMAROV; HOLCOMB, 2009; SHEFFI, 2015). The **area of the resilience triangle** summarizes the temporal effectiveness of each policy, while **response curves** show how TTR drops with **extended windows**, **off-dock**, **multi-gateway**, or **capacity options**.

The fifth stage incorporates **options and triggers**. Each scenario receives **activation rules**: "If *schedule reliability* $< X\%$ for Y weeks, **exercise option** on alternate service; if **queue** $> Z$ hours at gateway A, **divert** $X\%$ to gateway B; if **diesel** and **bunker** exceed bandwidths, **migrate** part of the

volume for **rail**.” These **contingent policies** are simulated to measure **TTR** and **total cost** under different shock **sequences**, recognizing that activation **timing** is as relevant as the choice of measure (SIMCHI-LEVI; KAMINSKY; SIMCHI-LEVI, 2008; CHRISTOPHER, 2016).

The sixth stage defines **signal posts** — **leading-consequent indicators** that monitor the proximity of a scenario—and **confidence thresholds** for triggering. Examples include **persistent declines** in trans-Pacific reliability (LPG/Sea-Intelligence), **abnormally increased docking times** (AIS), **variations in tariffs and sanctions** (Official Gazette), simultaneous **spikes in bunker/diesel prices** (EIA), and **driver shortage signals** (vacancies, highway *spot rates*). These signals feed **control towers** and **S&OP/S&OE**, reducing **decision-making latency** (IAPH, 2020; USDOT, 2020).

The seventh step is **validation and stress testing**. The digital twin needs to be **calibrated** with historical data (2018–2021) and **cross-validated** (e.g., to reproduce the 2021 reliability drop and observed queue times at gateways). Then, **extreme scenarios** are applied. (“plausible black swans”) to evaluate **TTR ranges** and **dominant bottlenecks** (WORLD BANK, 2020; NOTTEBOOM; RODRIGUE, 2021). Validation avoids **laboratory optima** and lends **credibility** to the model's use in capital and contract decisions.

The eighth stage integrates **governance**: scenarios leave the risk team and enter the **budget cycle** with **TTR/OTIF targets**, **VaR limits**, **mitigation portfolios**, and **responsible parties**; **playbooks** are versioned; post-event **AARs** feed *lessons learned*; and **KPIs** are included in **executive bonuses** (ISO 22301, 2019; SHEFFI, 2015). The result is a **repeatable process**, in which scenarios inform **where to integrate** (control) and **where to modularize** (options), with **data and contracts** serving as *rails* for execution.

3. Freight and Transmission Cost Structures for *Total Landed Cost* (TLC)

The starting point for modeling the impact of geopolitical shocks and volatility is to break down **freight costs** into their components and understand how each component propagates to the **Total Landed Cost (TLC)**. In **ocean freight**, in addition to the **base rate**, these include **BAF** (bunker adjustment factor), **CAF** (currency), **GRI/PSS** (general rate increase/peak season), **low sulfur/IMO 2020**, **congestion** surcharges, and **equipment imbalance**. In **land freight**, these include **drayage/chassis**, **rail/intermodal linehaul**, **port/terminal handling charges**, and **last mile charges**. Transversely, these include **demurrage/detention**, **storage**, **insurance**, **tariffs**, and **working capital** (UNCTAD, 2020; World Bank, 2020). In stress scenarios, small variations in **bunker/diesel** (EIA, 2021) and **schedule reliability** (Sea-Intelligence, 2021) produce **multiplicative effects** on the TLC, as they increase cycle times, require buffers and shift cargo to more expensive modes/practices (Chopra; Meindl, 2016).

The second step is to map freight **transmission mechanisms** to the **total cost of service**. As **lead times** and **dispersion** increase, **safety stock** and tied-up capital increase,

carrying cost; when **OTIF** falls, **air shipments** and **redispaching** increase , increasing the cost of operations; when **receiving windows** are missed, **contractual penalties** and **lost sales** arise . The **area of the resilience triangle** (fall × duration) transforms this degradation into a measurable **economic loss** , allowing **cents per TEU-mile** to be linked to **P&L margin points** (Sheffi, 2015; Ponomarov; Holcomb, 2009). Thus, scenario planning needs to **co-simulate** freight pricing, reliability, and tactical decisions (buffers, diversion, capacity options) to capture the **full effect**.

In the **ocean, bunker** shocks alter **BAF** in near-real time, but their net impact depends on the **equipment mix, routes** , and flow **commuting : imbalanced** trades suffer additional **repositioning surcharges**; trades with **multiple transshipments** are more sensitive to **congestion** and prolonged **GRI** (UNCTAD, 2020; Notteboom; Rodrigue, 2021). In **sanctions/export control** scenarios , "**forbidden paths**" create longer routes, change **the energy intensity** of the chain, and shift the **slot allocation** balance between alliances, affecting **priority** and **rollover**. These effects require **response curves** per service to estimate **how much TLC increases** for each lost **reliability point** .

In **North American intermodal, drayage/chassis constraints** and **rail linehaul** act as **amplifiers** of the TLC. The lack of **chassis** increases **wait time** and **detention; driver shortages** and **hours-of-service rules** put pressure on **spot rates**; limited **rail slots** increase **transit time** and **variance** (USDOT, 2020; OECD/ITF, 2016). In peak scenarios, **transloads** from 40' to 53' and **transfers** between ramps add handling and risk of damage; however, when well-timed, they reduce the **cost per useful mile** over long distances. Models should capture this **trade-off** and test **triggers** to switch between **all-water East Coast** and **land-bridge West Coast** according to **TTR** and **incremental cost**.

A critical transmission vector is **demurrage/detention**. In systemic congestion, linear charging policies generate **injustice** and encourage box **hoarding** , increasing **underutilization** and **premium freight; conditional** policies with **exemptions when the root cause is terminal/hinterland** reduce **dead costs** and free up **equipment** (World Bank, 2020; IAPH, 2020). In these scenarios, it is necessary to parameterize **alternative rules** and measure how much **TTR** and **TLC** change when governance shifts from **uniform punishment** to **pro-fluidity incentives** (Drewry, 2021). When simulating, it is observed that a few dollars less in detention produces **hundreds of dollars** in **avoided loss** per container.

Energy connects geopolitics and freight to the FTA. **Bunker** and **diesel** are **correlated** in global shocks, and simultaneous spikes raise **BAF** and **road linehaul**, shifting the **cost frontier** . between road and **rail/intermodal; jet-A** sets the **air cargo** price for contingency shipments (EIA, 2021; UNCTAD, 2020). Scenarios should include **price bands** with **tariff elasticities** by mode and modal shift **rules** , so that the simulation captures when

It is cheaper **to fly** part of the critical SKU mix than **to miss the sales window**, and when it is better **to stock up** for a few days than to pay **premium shipping**.

Another transmission channel is **compliance and tariffs**. **Sanctions and tariffs** reconfigure **BOMs** and **origins**; **export controls** on high-tech inputs create **indirect routes** or force **substitution of suppliers** with different **lead times** and prices, increasing costs and **quality risks** (UNCTAD, 2020; Notteboom; Rodrigue, 2021). The FTA must reflect **administrative costs** (licenses, audits, tariff classification), and **origin audit** overheads . (USMCA rules) and **scale losses** when the portfolio is fragmented to pursue **regulatory resilience**. In practice, **real options** (slots, gateways, suppliers) mitigate part of this cost when **triggers** activate previously qualified **replacement plans** (Simchi-Levi; Kaminsky; Simchi-Levi, 2008).

In **organizational terms**, TLC only enters decision-making when **metrics** and **processes** convert **logistical cents into margin points** and **S&OP/S&OE priorities**. **Control towers** They must present **incremental TLC by scenario** and **avoided loss** by measure (extended windows, off-dock, *multi-gateway*, capacity option), with **thresholds** that trigger actions without ad hoc debate (IAPH, 2020; ISO 22301, 2019). The **business case** ceases to be "expensive freight" and becomes "**preserved margin** and **reduced TTR**," language that allows for rigorous **approval of resilience capex/opex** (Sheffi, 2015).

Finally, TLC modeling must incorporate **SKU/customer heterogeneity**: **time-sensitive** items have high **time value** and justify **premium** or **air freight**; **commoditized** items tolerate **strategic inventories** and longer **lead times** . **ABC curves for value and criticality**, coupled with **differentiated service policies**, prevent uniform solutions that **burn cash** without increasing resilience. In short, the TLC in these scenarios functions as a **unified dashboard** where freight, reliability, and tactical decisions converge to guide efficient mitigation **portfolios** (Chopra; Meindl, 2016; Sea-Intelligence, 2021).

4. Geopolitical risk matrices and design of alternative routes (*gateways, all-water, land-bridge and nearshoring*)

The construction of **geopolitical risk matrices** begins by **categorizing shocks** that affect US supply chains: (i) disputes and sanctions between major economies (US–China; Russia; Iran), (ii) **bottlenecks at chokepoints** (Suez, Panama, Strait of Malacca, Taiwan Strait, Bab el-Mandeb), (iii) **climate** and **labor** events affecting gateways (Gulf hurricanes, coastal strikes), (iv) **cyber incidents** and **compliance** (export controls), and (v) **energy fluctuations** that reprice modes (UNCTAD, 2020; USDOT, 2020). For each class, **probability, impact, detectability** , and **warning time** are assessed , defining **signposts** and **triggers** for activating alternative routes (Sea-Intelligence, 2021; ISO 22301, 2019). The objective is not to predict the event, but **to pre-agree on viable responses** .

In the **trans-Pacific**, alternatives range from **West Coast land-bridge** (LA/LB, Oakland, Tacoma/Seattle) to **all-water East/Gulf** (NY/NJ, Savannah, Charleston, Houston). Congestion/labor shocks in LA / LB can trigger **all-water diversions** to the East, at the cost of **greater ocean traffic** and **lower land variance**; shocks in **Panama** or **Atlantic cyclones** can rebalance in favor of the **West Coast** with deep **rail linehaul** (USDOT, 2020; Notteboom; Rodrigue, 2021). The optimal choice depends on relative **TTR**, **total freight**, and **rail capacity**; therefore, matrices should **co-simulate** ports, canals, and **rail slots** to determine **target shares** per gateway under different regimes.

In the **transatlantic** and **Americas**, the **Eastern/Gulf** (NY/NJ, Norfolk, Savannah, Houston) and **Gulf/Mexico** gateways form the backbone. **Hurricanes** and **floods** impose seasonal **risk windows**; **security policies** in the Gulf can reduce **throughput**; **congestion** in NY/NJ redistributes calls to the **Southeast**. In parallel, **nearshoring** to **Mexico** and **Central America** adds **land optionality** (truck/rail under USMCA) and reduces exposure to **ocean chokepoints**, at the expense of **institutional risks** and cross- **border capacity** (OECD/ITF, 2016; USDOT, 2020). Headquarters must quantify when **transferring SKUs** nearshore preserves **margin** and **service level**.

On the **global chokepoint** axis, **Suez** and **Panama** are dominant variables. The **partial closure of Suez** induces **circumnavigation**, saving **days** and **bunker costs**, affecting **Asia-East US routes** via the **Med/Atlantic**; restrictions in **Panama** shift services to **LA/LB** or **all-water via Suez/Cape Town**, increasing **variance** (Notteboom; Rodrigue, 2021; UNCTAD, 2020). **Signals** such as **lake levels** in Panama, **AIS traffic**, and **anchorage queues** act as **diversion triggers**. In critical scenarios, **transshipment** via **Canada** (Prince Rupert/Vancouver) with **rail** to the Midwest emerges as a **bypass** with competitive TTR.

The **China+1** matrix considers **partial** production relocation to **Vietnam, India, Indonesia, Mexico**, and **the US**. This relocation changes **ocean times, tariff profiles, regulatory risk**, and **modal capacity**. For example, an **all-water India-US trade** via **Suez** is sensitive to shocks in this canal but reduces exposure to **LA/LB**; a **Mexico-US trade** reduces **capital costs** due to a **short lead time** but requires **border infrastructure** and **security** (USDOT, 2020; UNCTAD, 2020). The matrix quantifies **FTAs** and **TTRs** by SKU based on **origin mix** and guides transition **schedules** with **ramp-ups** and **bridge stocks**.

Labor and climate risks require seasonal maps and **mitigation windows**. Coastal **strikes** present **signals** (negotiation impasses) that allow for **pre-positioning inventory** or **advance bookings**; **hurricane seasons** in the Gulf and Atlantic trigger **extended gate hours, off-dock**, and **priority** for **time-sensitive** cargo (USDOT, 2020; ISO 22301, 2019). **Digital twins** with **weather** layers and **union calendars** enable **stress tests** with **playbooks**. structured, reducing **latency** and **loss**.

Cyber and compliance comprise the cross-cutting layer. Attacks on **TOS/PCS** and logistics **pipelines** can disrupt services without physical damage; **export controls** reconfigure **BOMs** and **routes**.

overnight (IAPH, 2020; UNCTAD, 2020). The matrices include **cyber hardening** (redundancy, disconnected backups) and "clean" compliance **paths** for critical SKUs, with **documentation ready**. **Triggers:** vulnerability alerts, regulatory changes, sectoral incidents.

Finally, **alternative route design** is a **portfolio approach**, not a **silver bullet**. Geopolitical matrices prescribe **target participations** per gateway and **diversion options** with **clear thresholds** (decrease in **schedule reliability**, **queue**, **bunker/diesel**), combining **contractual optionalities** (slots, *box pools*), **structural buffers** (off-dock/dry ports), and **data** (PCS/control towers) to **reduce TTR** and **protect margin** (Simchi-Levi; Kaminsky; Simchi-Levi, 2008; Sea-Intelligence, 2021; USDOT, 2020). Success is measured by the area of the triangle of reduced **resilience**, sustained OTIF, and **stabilized TLC** in adverse scenarios.

5. Mitigation portfolios and *real options*: efficient buffer frontiers, multi-gateway and elastic contracts

The formulation of a **mitigation portfolio** is based on the principle that no single intervention dominates in all scenarios; the objective is to compose an **efficient portfolio** that minimizes the **area of the resilience triangle** (downturn × duration) at the lowest possible cost of capital. In practice, this involves combining **physical buffers** (bridge stocks, deliberate idle capacity), **structural buffers**, and (multi-gateway, dry ports/off-dock, modal redundancy), **informational buffers** (PCS, control towers, arrival forecasts), and **contractual options** (capacity reservations, *box pools*, deviation clauses) that can be **activated by** previously agreed triggers (SHEFFI, 2015; CHOPRA; MEINDL, 2016). The optimal portfolio differs by SKU and corridor, as **the value of time**, **substitutability**, and **criticality** vary substantially between product families and regions (PONOMAROV; HOLCOMB, 2009).

The **real options** lens helps price decisions in the context of **freight volatility** and **geopolitical shocks**: paying a **premium** today for a **slot option** or a **multi-gateway contract** is analogous to acquiring the right, not the obligation, to exercise capacity when **signposts** signal reliability degradation or cost *spikes* (SIMCHI-LEVI; KAMINSKY; SIMCHI-LEVI, 2008; CHRISTOPHER, 2016). The expected value of this option increases with the **underlying volatility** (*bunker/diesel*, *schedule reliability*) and the **disruption cost**, so that highly critical SKUs justify higher premiums. This approach disciplines the conversation with finance, as it translates "TTR reduction" into **avoided loss** per dollar invested, comparable to the CAPEX of warehouses, yards, and automation (SHEFFI, 2015).

Physical buffers have merit where **lead time** is long, replacement is low, and **arrival uncertainty** dominates; however, they immobilize **working capital** and are at **risk of obsolescence**, requiring strict governance via **ABC curves** and **continuous review** policies (CHOPRA; MEINDL, 2016).

In contrast, **structural buffers** — such as **multi-gateway** and **off-dock** — preserve **operational optionality** with lower loading costs, as long as **standards**

technical aspects (packaging, labeling, EDI/API) make the replacement **plug-and-play** (OECD/ITF, 2016; WORLD BANK, 2020). The *trade-off* between “stock” and “structure” is, therefore, contingent on the risk profile and the **elasticity of** transportation available in each corridor (NOTTEBOOM; RODRIGUE, 2021).

In **port and intermodal environments** subject to **congestion**, the portfolio should include **short-term tactics** (extended windows, yard reslotting, SLA/time value prioritization) that reduce backlogs quickly, and **medium-term interventions** (dry ports, seasonal rail contracts, regional *box pools*) that reduce **variance** without excessively increasing fixed costs (WORLD BANK, 2020; IAPH, 2020). For the **long term, modular** capabilities (phased berths, selective automation, scalable rail corridors) avoid **rigidity** and allow growth in blocks, keeping **TTR** under control in repeated shocks (IVANOV; DOLGUI, 2020). Efficiency arises from the **complementarity** between time horizons.

The **contractual** dimension of the portfolio organizes **who pays what, when, and why**. **Contingency SLAs** with **objective triggers** (drop in *schedule reliability*, docking queues, *truck turn time*, used/planned *rail slot*) activate **capacity reservations, multi-gateway diversions** , and **conditional demurrage/detention exemptions**, reducing litigation and **decision-making latency** (SEA-INTELLIGENCE, 2021; IAPH, 2020). In severe scenarios, **reliability indexing** and **gain-sharing mechanisms** align incentives to recover service faster, as part of the **bonus/penalty** is converted into **operational actions** (extra windows, additional trains) that compress the **resilience triangle** (WORLD BANK, 2020; CHRISTOPHER, 2016).

Corridor **digital twins** —coupling **DES/SD/ABM** with **AIS/TOS/PCS** data —serve to create efficient portfolio **frontiers** : for each combination of **physical/structural buffers** and **contractual options, TTS/TTR, OTIF, demurrage/detention** , and **TLC** are estimated under stress trajectories (IVANOV; DOLGUI, 2020). By plotting **impact/cost curves**, decision-makers identify “leverage points” (e.g., +1 train/day reduces TTR by 22%; +1 night window reduces *truck turntime* by 18%; +X% of *box pool* reduces *freight premium* by Y), replacing opinions with simulated **evidence** (SHEFFI, 2015). This discipline facilitates **CAPEX/OPEX** approval and prioritizes **quick wins**.

The portfolio must also reflect **spatial heterogeneity** and **seasonality**. During **peak periods** (harvests, *peak season*), measures such as **dynamic scheduling, valley bands, off-dock pickup** , and **seasonal rail contracts** have greater **elasticity** ; off-peak periods, **equipment pools** and **coordinated repositioning** capture access gains, mitigating **underutilization** and container **imbalances** (UNCTAD, 2020; DREWRY, 2021). On the **geopolitical map**, portfolios with **targeted holdings** by gateway and **origin mix** (China+1, nearshoring) reduce **risk correlations** and shorten **lead times**, protecting the **FTA** under sanctions and energy shocks (USDOT, 2020; NOTTEBOOM; RODRIGUE, 2021).

Ultimately, the portfolio's **go/no-go** should be governed by **risk limits** and **resilience targets**. **Operational VaR** and **Expected Shortfall** of service indicators (OTIF, *backlog clearing*) define **tolerable ranges**; **TTR/TTS targets** by SKU and corridor become **restrictions of the**

S&OP/S&OE thresholds (LPG below X%, bunker/diesel above the band) **trigger** the exercise of options and **reconfigure** flows according to the *playbook* (ISO 22301, 2019; SEA-INTELLIGENCE, 2021). Thus, the portfolio is more than a set of ideas: it is an **operable mechanism** that transforms **signals** into **action** with clear *timing* and responsibilities.

6. Governance, Data, and Activation *Signposts* : From PCS and Control Towers to Trigger-Driven S&OP

Resilience governance translates scenarios and portfolios into **decision-making routines**. At the core, **Port Community Systems (PCS)** and **Digital Single Windows** consolidate **operational and documentary data** (ETA/ETD, queues, productivity, inspections) using **open standards** and **secure APIs**, reducing **information asymmetry** and **downtime** (IAPH, 2020; OECD/ITF, 2016). On this layer, **interorganizational control towers integrate** TOS /WMS/TMS/rail slots and **reliability indicators** (GLP/Sea-Intelligence), displaying trigger-driven **KPIs/KRIs**.

(e.g., *truck turn time* > X, *dwell* > Y, docking queue > Z) that trigger **playbooks** pre-authorized — open windows, prioritize critical loads, activate **off-dock**, recommend **multi-gateway diversion** (WORLD BANK, 2020; SEA-INTELLIGENCE, 2021).

The definition of **signposts** —precursor signals that anticipate the approach of a scenario—is the link between **intelligence** and **operations**. Examples include **persistent declines** in *schedule reliability* by alliance/service, bunker /**diesel** out-of-band (EIA) **spikes**, and **abnormal increases**. **anchoring time** at critical gateways (AIS), **regulatory alerts** on **sanctions/export controls**, **restrictions in Panama/Suez** and **driver shortage indicators** (vacancies, *spot rates* road users) (USDOT, 2020; UNCTAD, 2020; SEA-INTELLIGENCE, 2021). Each signpost needs a **numerical threshold**, **responsible person**, and **default action**; without this engineering, detection becomes curiosity and not **decision** (ISO 22301, 2019).

Data dictionaries and **calculation methodologies** are essential for **comparisons** make sense: *dwell* by cargo/service type, *truck turn time* by window, planned vs. actual *rail utilization*, delay **dispersion**, error **persistence** by service, simulated **TTR** by intervention (OECD/ITF, 2016). **Reconciliation cycles** (TOS ÷ PCS ÷ WMS/TMS) and **audit logs** support **accountability** and limit contractual disputes, especially when **reliability indexing** and **conditional demurrage/detention exemptions** come *into* play (IAPH, 2020; WORLD BANK, 2020). **Data quality** is not an accessory: it is **operational capacity**.

Trigger-driven **S&OP/S&OE orchestration** connects the control tower to **execution**. In **S&OP**, **TTR/TTS targets**, **VaR limits**, and target gateway and mode **mixes** are defined by SKU; in **S&OE**, **playbooks** are applied when **signposts** cross thresholds— **exercising** slot options, **migrating sailing** to *all-water* or *land-bridge*, **pre-positioning inventory**, **activating** dry ports, and **extending windows** (SIMCHI-LEVI; KAMINSKY; SIMCHI-LEVI, 2008; CHRISTOPHER, 2016).

Short rituals (daily briefings, weekly *war rooms*) avoid **decision-making latency** and **pace** adaptation, with post-event **AARs** generating **continuous improvement** (ISO 22301, 2019; SHEFFI, 2015).

The **contractual-informational** layer requires **pre-authorization** to function in minutes, not weeks: who can **divert** X% of the portfolio? Who **accesses** capacity reserves? Who **signs** conditional *demurrage* exemption ? What **data** is published to **audit** the decision? Without these **rights of action** and paper **limits** , the control tower becomes an observation panel (IAPH, 2020; WORLD BANK, 2020). **Segregation of duties** and **compliance** preserve integrity, especially in environments with **alliances** and integrated operators (OECD/ITF, 2016).

Cyber resilience and **continuity** are cross-cutting conditions. **Disconnected** TOS/PCS backups, **contingency plans** for manual *fallback* , and periodic **restoration tests** reduce the chance that a **cyber incident** will neutralize governance at the worst possible time (ISO 22301, 2019). In geopolitical scenarios, **disruption targets** may include digital infrastructure; therefore, **redundant telemetry**, **degraded access** , and alternative **communication protocols** (radio, SMS) must be included in the **playbook**, with regular **training** (SHEFFI, 2015).

Selective transparency with the ecosystem strengthens the legitimacy of decisions. Public turnaround /**dwell**/ **reliability dashboards** with explicit methodology, **barometers** Periodic (IAPH) and corridor **performance reports** support **accountability** and **alignment** among actors, reducing the temptation of **particular solutions** that concentrate gains and socialize losses (IAPH, 2020; WORLD BANK, 2020). In concentrated markets, data **aggregation/delay** preserves competition while providing **common coordinates** for action (OECD/ITF, 2016; HARALAMBIDES, 2019).

Training closes the loop: teams capable of reading **signposts**, operating **digital twins**, and translating **metrics** into **decisions** are as important as cranes and rails. **Training** programs for **queues and networks**, **logistics contracts**, **S&OP/S&OE** , and **risk analysis** must be continuous, with **living labs** in terminals and **simulations** integrated into the routine (CHRISTOPHER, 2016; IVANOV; DOLGUI, 2020). Bonuses tied to **reduced TTR**, **preserved OTIF** , and **reduced demurrage/ detention** align behavior with the goal of **measurable resilience** (SHEFFI, 2015).

Finally, **governance**, **data**, and **signposts** only create value when **anchored to budgets and targets**. **KPIs/ KRIs** are included in the **annual plan**, and **portfolios** receive funding with **phase gates**. conditioned on **TTR reduction** and **avoided loss**, and **quarterly reviews** adjust **thresholds** as the environment changes (USDOT, 2020; ISO 22301, 2019). Thus, the system ceases to depend on “operational heroes” and begins to operate under an **Operational Resilience Regime** reproducible, where **signals** become **actions** and **actions** become auditable **metrics** .

7. Empirical Validation and Learning: Evidence from US Corridors Under Geopolitical Shock and Freight Volatility

The usefulness of scenario planning depends on its **external validity**: models and *playbooks* need to replicate observed patterns and explain residual variability in **TTR**, **OTIF**, and **TLC** in real shocks. In the **trans-Pacific**, the combination of **declining schedule reliability**, **docking queues**, and **chassis/driver constraints** generated simultaneous degradations in **turnaround** and **dwell**, an effect predicted by **interconnected queue** models and **percolation when** multiple nodes operate with $\gamma > 1$ (Sea-Intelligence, 2021; World Bank, 2020; Ivanov; Dolgui, 2020). In retrospective tests, digital twins that coupled **AIS/TOS/PCS data** and **bunker/diesel bands** reproduced **backlog curves** and **delay windows** with acceptable error, reinforcing the adequacy of the framework for mitigation **decisions** (Notteboom; Rodrigue, 2021; UNCTAD, 2020).

In the **West ÿ Interior/Midwest land-bridge**, **rail capacity** and adherence to drayage **schedules explained** differences in TTR between **similar ocean freight routes**, validating the premise of **intermodal coupling** and the need for **inland KRIs** (truck turn time, utilized/planned rail *slot*) in the resilience dashboard (USDOT, 2020; OECD/ITF, 2016). In *what-if exercises*, the activation of **extended windows** and **additional trains** anticipated by **signposts** (decrease in reliability due to alliance; increase in *anchor time*) reduced **backlog clearing** by tens of hours, with significant **avoided losses** in the **FTA** (Sea-Intelligence, 2021; World Bank, 2020). These results support the inclusion of **operational triggers** in contracts and S&OE.

In the **all-water scenario for the East Coast/Gulf**, scenarios combining **pressured Panama** and **Atlantic weather** showed that **real gateway diversification** mitigates risk but only preserves **margin** when accompanied by **off-dock/dry ports** and time-value prioritization **SOPs**. Otherwise, the ocean gain is offset by **spillback** at yards and *gates* (Notteboom; Pallis, 2020; World Bank, 2020). Simulations indicated that technical **standards** (packaging, labeling, EDI/API) reduce the *ramp-up* of alternative routes by weeks, justifying **low-CAPE** investments with a high impact on **TTR** (OECD/ITF, 2016; Christopher, 2016). This finding reinforces the thesis of **modularity** as a lever of resilience.

In **freight costs**, the **energy ÿ tariffs ÿ FTA** link was validated by parameterizing **BAF/diesel/jet-A** with **EIA** series and elasticities by mode; simultaneous *spikes* increased **premium freight**, activating *playbooks* that migrated part of the **road ÿ rail/intermodal** mix and **ocean ÿ air** for **time-sensitive SKUs**, with a positive impact on **OTIF** and **preserved revenue** (EIA, 2021; UNCTAD, 2020; Chopra; Meindl, 2016). The **opportunity cost** of not activating the option—measured by **the area of the resilience triangle**—exceeded the premium paid for **capacity options**, corroborating the **economics** of volatility options (Simchi-Levi; Kaminsky; Simchi-Levi, 2008; Sheffi, 2015).

In the contractual dimension, case studies with **reliability indexing** and **contingency SLAs** have shown a reduction in **litigation** and **decision latency** when **metric dictionaries** and

APIs were coded ex-ante in **PCS**; the absence of these elements generated **version disputes** that postponed actions during the critical window (IAPH, 2020; World Bank, 2020). The **conditional exemption from demurrage/ detention** when the root cause was terminal/hinterland accelerated **box turnover** and improved **equipment availability**, reducing **premium freight rates** in congested corridors (UNCTAD, 2020; Drewry, 2021). These results support **pro-fluidity policies** in a crisis.

In **nearshoring** (USMCA), pilots with a **partial mix of origins** showed a decrease in **working capital** and **lead time**, with lower **TTR** under ocean shocks, but with **institutional risks** and **cross-border restrictions** that require an **interoperable Single Window** and a reliable rail **slot**; the **net advantage** emerged when **compliance** and **capacity** were resolved through **bilateral agreements** and **modular investments** (USDOT, 2020; OECD/ITF, 2016). The lesson is that **risk substitution** must be accompanied by **standards and governance** to avoid exchanging one bottleneck for another (Haralambides, 2019; Rodrigue, 2020).

In **cyber resilience**, sectoral incidents have shown that **disconnected backups** and **fallback plans** preserve **governance** when **PCS/TOS** are affected; tabletop exercises have reduced **restoration time** and **information loss**, keeping **S&OE** operational in degraded mode (ISO 22301, 2019; Sheffi, 2015). In terms of scenarios, the cyber layer was integrated as a **cross-cutting shock** with **alternative communication** triggers and degraded **decision rights**, validating the principle that **data** is critical infrastructure for resilience (IAPH, 2020; World Bank, 2020).

Regarding **value measurement**, *dashboards* that translated **TTR/OTIF** and **freight** into **TLC** and **Operational VaR** accelerated **CAPEX/OPEX approval**, shifting the discourse from "additional cost" to "**avoided loss** and **preserved margin**," a language that bridges operations and finance (Ponomarov; Holcomb, 2009; Sheffi, 2015). In the quarterly revaluation, portfolios with **structural buffers** (multi-gateway, off-dock) and **contractual options** dominated arrangements based solely on **physical inventories**, especially for SKUs with **high time value**.

(Christopher, 2016; Sea-Intelligence, 2021). The empirical evidence, therefore, aligns with the model's theses.

Finally, **institutional learning** —via **AARs** and **playbook versions** —proved crucial to maintaining **dynamic viability**: teams that ran **simulations** and **trials** reduced **timing errors** in option activation and improved **backlog clearing** in subsequent waves (ISO 22301, 2019; Ivanov; Dolgui, 2020). The *insight* is clear: scenarios are **practiced capability**, not documentation; their effectiveness grows with **deliberate repetition**, **multilateral governance**, and **public metrics**.

8. Roadmap and governance: from proof of *concept* to resilience operational regime

The **roadmap** begins with a **materiality diagnosis**: mapping **critical corridors, A/B SKUs by time value, probable bottlenecks** (ports, rail, *drayage*, compliance) and **energy dependencies**, producing a **risk register** with **owners, KRIs/KPIs** and **TTR/TTS targets**. (USDOT, 2020; ISO 22301, 2019). In parallel, define **axes of uncertainty** for the scenario portfolio (geopolitics; freight/energy; intermodal capacity) and **storylines** coherent decisions that feed the **digital twin** (Wack, 1985; Schoemaker, 1995). The result is a **decision map** that links **triggers** to **options** (deviation, capacity reserves, windows) and **buffers** (bridge stocks, off-dock).

In **Phase 1 (0–90 days)**, build the **minimum viable dashboard**: integrate **AIS/ETA, TOS, PCS, WMS/TMS**, and **rail data** to display **reliability by service, queue/anchorage, turnaround/dwell, truck turn time**, rail slot, and **container availability**, with a **metric dictionary** and agreed-upon **data SLA** (IAPH, 2020; World Bank, 2020). In parallel, **prototype** the **digital twin** of a pilot corridor (e.g., trans-Pacific ÷ Midwest) and run **baseline scenarios**, calibrating parameters with 2018–2021 series (Sea-Intelligence, 2021; Ivanov; Dolgui, 2020). This basis allows for **quick decisions** at the first seasonal peak.

In **Phase 2 (90–180 days)**, institutionalize an **interorganizational control tower** with **preauthorized decision rights** and codified **playbooks**: **open windows, prioritize critical loads, activate off-dock, divert X%** to an alternative gateway when **thresholds** are crossed (ISO 22301, 2019; Christopher, 2016). In contracts, implement **contingency SLAs, reliability indexing**, and **capacity options** for relevant services and gateways; in equipment, negotiate regional **pools/box interchange** with **neutral governance** (Drewry, 2021; UNCTAD, 2020). The emphasis is on **reducing decision latency** in shocks.

In **Phase 3 (6–12 months)**, scale **structural buffers: dry ports, retroport terminals, chassis cohorts**, and **seasonal rail contracts**, prioritizing corridors where **TTR** is most sensitive to **yard evacuation** and **linehaul** (World Bank, 2020; OECD/ITF, 2016). In parallel, standardize **packaging/labeling/messaging** for **plug-and-play substitutability** between gateways and operators, reducing **requalification time** and diversion **costs** (Christopher, 2016; Notteboom; Pallis, 2020). This phase consolidates **true geographic redundancy**.

In **Phase 4 (12–24 months)**, invest in **modular capacity** and **selective automation** where twin **response curves** indicate a **high marginal gain** in **TTR** per unit of capital: **phased berths, additional STS, partial yard automation, scalable rail corridors, and off-dock logistics zones** (Ivanov; Dolgui, 2020; World Bank, 2020). Linking **availability payments** to **contingency SLAs** reduces demand risk and accelerates *payback*, transforming resilience into a **bankable asset** (Sheffi, 2015). Governance should include **phase gates** and **quarterly reviews** for **avoided loss**.

The **regulatory framework** involves **Single Window, harmonization of consents** and **public goals** (turnaround, *dwell*, reliability), with **open data standards** and **periodic barometers** to reduce **political noise** and align incentives (USDOT, 2020; IAPH, 2020; OECD/ITF, 2016). In **cross-border cooperation** (USMCA), prioritize document **interoperability** and **rail slots**; in **chokepoints** (Panama/Suez), incorporate hydrological and **AIS traffic** signposts to diversion *playbooks* (Notteboom; Rodrigue, 2021; UNCTAD, 2020). The common thread is that **data and rules** are as critical as **cranes and rails**.

In **human capital**, create **training paths** for reading **signposts**, operating **digital twins, options contracts**, and **trigger-based S&OP/S&OE**; run monthly **simulations** and **AARs** post-peak to fix learning (Christopher, 2016; ISO 22301, 2019). **Bonuses** linked to **reduced TTR, preserved OTIF**, and **reduced demurrage/detention** align behavior with **measurable resilience** (Sheffi, 2015). The desired culture favors **data discipline, pre-authorized execution**, and **multilateral cooperation**.

In **finance**, incorporate **Operational VaR** and **Expected Shortfall** of service into the **budget cycle** and approve **mitigation portfolios** for **avoided loss**; structure **parametric insurance** and **capacity options** with **verifiable triggers** (LPG, queues, *dwell*), and use the twin to **price the rational premium** (Ponomarov; Holcomb, 2009; Sea-Intelligence, 2021). Reports to the board should display **efficient boundaries** between **physical inventory, structural buffers**, and **options**, with **TTR/OTIF targets** as constraints, not *nice-to-haves* (Simchi-Levi; Kaminsky; Simchi-Levi, 2008; Sheffi, 2015).

Finally, the **resilience operational regime** is consolidated when **signals become actions** and **actions become metrics** under **predefined governance: signposts** monitored by the tower; **triggers** triggering **playbooks; auditable data** in **PCS/Single Window; contracts** with **SLAs/options/conditional waivers; AARs** feeding back into models; and **public goals** aligning ecosystems (World Bank, 2020; IAPH, 2020; ISO 22301, 2019). This cycle closes the gap between **anticipation** and **execution**, reducing **the area of the resilience triangle** and stabilizing **TLC**. in adverse scenarios (Notteboom; Rodrigue, 2021; Sea-Intelligence, 2021).

Conclusion

The research developed throughout this article has argued that **scenario planning** is more than a narrative exercise: it is an **operational mechanism** for reducing the exposure of U.S. supply chains to **geopolitical disruptions** and **freight cost volatility**, provided it connects plausible storylines to **quantitative models** and **decision triggers** coupled with S&OP/S&OE. By combining **discrete-event simulation, system and agent dynamics** with **Monte Carlo**, and indicators such as **TTS/TTR, OTIF, Operational VaR, and avoided loss**, we demonstrate that the practical utility of scenarios increases when their assumptions are anchored in **measurable signalposts** (persistent decline in *schedule reliability*, *bunker/diesel spikes*, *AIS queuing/anchoring*, regulatory changes), all translated into **playbooks**.

preauthorized (Wack, 1985; Schoemaker, 1995; Sheffi, 2015; Sea-Intelligence, 2021; USDOT, 2020).

In terms of **risk phenomenology**, we show that apparently exogenous shocks — Trade sanctions, *chokepoint events*, strikes, and extreme weather events—all materialize in **port and intermodal links** as **queues, productivity losses, and increased variance**, triggering delay **percolation** in networks with high centrality and undersized buffers. **Interconnected queuing** theory and **network science** explain why small productivity drops at multiple nodes (ȳ1) produce **superlinear** backlog growth, expanding the **area of the resilience triangle** and degrading the **FTA** beyond what historical averages suggest (Ivanov; Dolgui, 2020; World Bank, 2020; Notteboom; Rodrigue, 2021). When well-constructed, the scenario anticipates this critical regime and determines **where to decouple** and **when to deviate**.

In the **economic** vector, the breakdown of freight into its **tariff components** (base rate, BAF/CAF, GRI/PSS, congestion, *equipment imbalance*) and land costs (drayage/chassis, rail linehaul, *terminal handling, last mile*) reveals **transmission mechanisms** up to the **Total Landed Cost**, including via **safety stocks, working capital, contingency shipments**, and **contractual penalties** for missed windows. The integration of **energy ȳ tariff ȳ TLC** —with bands for bunker/diesel/jet-A and elasticities by mode— proved critical for valuing **real options** (capacity reservations, multi-gateway, *box pools*) and for dimensioning **structural buffers** that preserve **margin** when reliability degrades (UNCTAD, 2020; EIA, 2021; Chopra; Meindl, 2016; Sheffi, 2015).

At the geographic-strategic level, the **risk matrices** by corridor (trans-Pacific, trans-Atlantic, Gulf/Americas) and by **chokepoints** (Panama, Suez, Strait of Malacca, Taiwan Strait) indicated that **real diversification** of gateways combined with **off-dock/dry ports** and **technical standardization** (packaging, labeling, EDI/APIs) creates **operational optionality** with competitive total cost. In parallel, **China+1** and **USMCA nearshoring** reduce exposure to critical ocean routes, but only deliver net resilience when accompanied by **document interoperability** and **cross-border capacity** (USDOT, 2020; OECD/ITF, 2016; Notteboom; Pallis, 2020; Rodrigue, 2020). Scenarios allow **sequencing** these transitions and **pricing ramp-ups** with *bridging stock*.

Data governance has emerged as the infrastructure for predictability. **Port Community Systems** and **Single Digital Windows** have reduced **information latency** and **noise** between stakeholders, enabling **inter-organizational control towers with pre-authorized rights** to open windows, prioritize critical loads, trigger **off-dock** operations, and recommend **diversions**, all while relying on **metric dictionaries, secure APIs**, and **audit logs**. Experience gathered from port barometers and performance reports indicates that communities with **open data standards** and **regular** KPI publications weathered the 2019–2021 volatility better, making **SLAs indexed**

reliability and operationalizable and auditable **conditional demurrage/detention exemptions** (IAPH, 2020; World Bank, 2020; OECD/ITF, 2016).

In the **contractual-incentive domain**, we argue and illustrate that **contingency SLAs** with **objective triggers, capacity options**, and **gain-sharing mechanisms** convert scenarios into actionable **operational insurance**, reducing **decision latency** and **litigation** in critical windows. In severe scenarios, **interorganizational container pools** and **box interchange agreements** have proven effective in mitigating **equipment imbalances** and underutilization, freeing up slots for paying cargo and reducing **premium freight**—a result reinforced by root-cause-based **demurrage/detention** policies (Drewry, 2021; Clarksons Research, 2021; UNCTAD, 2020). Contractual consistency, therefore, enhances process engineering.

The **value** analysis showed that decisions need to shift from “cost per TEU” to **avoided loss**. and **reduced TTR** per unit of capital, comparing **efficient frontiers** between **physical inventories, structural buffers**, and **contractual options**. **Digital twins** calibrated with 2018–2021 series were crucial in translating **response curves** (e.g., +1 train/day, +1 overnight window, X% *box pool*) into **preserved OTIF, reduced demurrage/detention**, and **stabilized TLC**— a language that brings boards and operations closer together and facilitates **CAPEX/OPEX** approval with **Operational VaR** and **Expected Shortfall** criteria (Ponomarov; Holcomb, 2009; Sheffi, 2015; Ivanov; Dolgui, 2020).

In the **implementation roadmap**, we advocate a four-phase path: **(i)** minimum viable panel and pilot corridor twin; **(ii)** control tower with **rights of action, playbooks**, and **contracts** with SLAs/indexing/options; **(iii)** scaling of **structural buffers** (dry ports, off-dock, seasonal rail contracts) and **standardization** for **plug-and-play replacement**; **(iv)** investments in **modular capacity and selective automation** anchored in **availability payments** and TTR targets. The guiding principle is a **Resilience Operational Regime** where **signals become actions** and **actions become metrics** under **predefined governance** (ISO 22301, 2019; USDOT, 2020; World Bank, 2020).

The **public and transboundary** dimension is inseparable from private performance: **disclosed performance targets, open data standards, regulatory harmonization**, and **interoperability agreements** (customs, phytosanitary, security) reduce the “border effect,” shorten systemic **TTR**, and create **legitimacy** for prioritization in scarcity. In parallel with the **climate agenda**, investments in **adaptation** (physical infrastructure) and **decarbonization** (shore power, yard electrification) have shown **reliability co-benefits**, reducing unplanned outages and increasing **energy redundancy** (Haralambides, 2019; World Bank, 2020; UNCTAD, 2020). Resilience, therefore, aligns with sustainability as an **ecosystem advantage**.

As a **research and practice agenda**, there are three tracks: **(a)** standardized methods for **pricing real options** in logistics contracts and *box pools* under freight volatility and geopolitical regimes; **(b)** operational integration of **digital twins** into **S&OP/S&OE**, with **signposts**

automated and **feedback** by *After Action Reviews*; (c) **ecosystem resilience** metrics that capture distributive and **reputational effects** beyond the firm, including under climate and cybernetic perspectives. The expected marginal gain lies in **reducing the gap** between *insight* and **execution** by standardizing how we prioritize **buffers, data, and contracts** (Sea-Intelligence, 2021; IAPH, 2020; ISO 22301, 2019).

In short, **planning scenarios** for North American chains means **designing responses** before the crisis: **where to integrate** to control what cannot fail, **how to modularize** to preserve **optionality**, **when to activate** options and **how much to invest** to **reduce TTR** and **preserve margin** under shocks. The proposed framework— **metric, modeled, and governed** —replaces improvisation with **resilience engineering**, transforming geopolitical and tariff variability into **manageable risk** and, by extension, into **repeatable competitive advantage** for companies and corridors that adopt it (Christopher, 2016; Notteboom; Rodrigue, 2021; USDOT, 2020; Sheffi, 2015).

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